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CORRECTION AND IMPROVEMENT OF THE INERTIAL-DAMPING COLLOCATION --ETC(U)

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ABSTRACT

An earlier version of the uncoupling technique referred to as the Inertial-Damping Collocation Approximation is shown to be improperly formulated, and a corrected, improved and simplified version is presented.

1. <u>Earlier Version of the IDCA</u>

If, for simplicity of presentation, it is assumed that the excitation involves no incident fluid velocity and no discontinuity in incident pressure, the Inertial-Damping Collocation Approximation (IDCA) presented in Refs. [1] and [2] may be written as*)

$$\ddot{q} - a\ddddot{q} = -\gamma^{-1}Q_1 + B\ddot{Q}_1 + C\ddddot{Q}_1 \tag{1}$$

$$\ddot{q} = DQ_2 - \alpha^{-1}\ddot{Q}_2 \tag{2}$$

$$Q = Q_1 + Q_2 \tag{3}$$

In Eqs. (1)-(3), a dot denotes differentiation with respect to time t, a superscript - 1 denotes an inverse, and

(i) α and γ, as discussed in Ref. [1], are, respectively, known diagonal damping and virtual mass matrices corresponding to appropriate orthogonal surface expansion functions.

(ii) a is a matrix intended to be used to make the IDCA go over to the Curved Wave Approximation (CWA) for short times (Ref. [2]).

(iii) q is the matrix of (modified) generalized coordinates for the normal shell displacement (corresponding to surface expansion functions, as opposed to shell modes).

(iv) Q_1 and Q_2 are, respectively, inertial and damping "components" of the generalized force Q corresponding to the radiated fluid pressure on the shell surface.

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*) It should be noted that in Eq. (1), and in what follows, the sign of the virtual mass matrix has been changed to produce a positive definite matrix.

(v) B, C and D are fitting matrices, to be determined by matching the steady-state response of a fluid cavity, having the same shape as the shell, at selected frequencies, with the response obtained using acoustic computer codes.

As shown in Ref. [2], the Doubly Asymptotic Approximation (DAA) may be written as

$$\ddot{q} = -\alpha^{-1}\dot{Q} - \gamma^{-1}Q \tag{4}$$

which, for short times (or high frequencies), becomes the Plane Wave Approximation (PWA)

$$Q = -\alpha\,\dot{q} \tag{5}$$

and, for long times (or low frequencies), goes to the Virtual Mass Approximation (VMA)

$$Q = -\gamma\,\ddot{q} \tag{6}$$

as it should.

If B, C, D and a are set equal to zero, Eqs. (1)-(3) lead to

$$Q = -\alpha\,\dot{q} - \gamma\,\ddot{q} \tag{7}$$

which does not go to the correct asymptotic relations. Furthermore, although using

$$a = -C\,\beta \tag{8}$$

in Eq. (1), as in Ref. [2], where β is a symmetric curvature matrix defined in Ref. [2], leads to the CWA when B and D are set equal to zero, an inertial component has been used to satisfy short-time damping behavior. This would cause a very poor match at high frequency in the relation between the generalized force and the inertial component of the acceleration as a function of frequency.

2. Corrected Version of the IDCA

Instead of Eqs. (1)-(3), an appropriate form is

$$\ddot{q}_1 - B\lambda \ddddot{q}_1 = -\gamma^{-1}Q + B\ddot{Q} \tag{9}$$

$$\ddot{q}_2 - D\varepsilon\dot{q}_2 = DQ - \alpha^{-1}\ddot{Q} \tag{10}$$

$$q = q_1 + q_2 \tag{11}$$

in which λ and ε are matrices introduced to permit the IDCA to approach the correct asymptotic limits. If B and D are set equal to zero, Eqs. (9)-(11) go to the DAA of Eq. (4) as they should.

3. Determination of B and D

On the surface of a fluid cavity having the same shape as the shell, apply the pressure

$$p_i(s, t) = P_i\, \psi_i(s) e^{\hat{i}\, \Omega_i t} \tag{12}$$

In Eq. (12), s denotes position on the shell surface, P_i is a constant, $\hat{i} = \sqrt{-1}$, Ω_i is an appropriately chosen fitting frequency, and $\psi_i(s)$ is one of the orthogonal surface expansion functions which satisfy

$$\int_A \psi_i \psi_j \, dA = \mu_i \, \delta_{ij} \tag{13}$$

where A is the surface area of the shell and δ_{ij} is the Kronecker delta.

The generalized forces corresponding to the pressure of Eq. (12) are

$$(Q_j)_i = \int_A p_i(s, t)\, \psi_j(s)\, dA \tag{14}$$

Using Eqs. (12) and (13), Eq. (14) becomes

$$(Q_j)_i = P_i \mu_j \delta_{ij} e^{\hat{i}\Omega_i t} \tag{15}$$

which yields

$$(Q_i)_i = P_i \mu_i e^{i\hat{\Omega}_i t} \equiv Q_i(t)$$
$$(Q_j)_i = 0, \; j \neq i \tag{16}$$

On the surface of the shell, the normal acceleration resulting from the excitation of Eq. (12) may be expressed as

$$\ddot{w}_i(s, t) = Q_i(t)\bar{A}_i(s) - \dot{Q}_i(t)\bar{\bar{A}}_i(s) \tag{17}$$

Since the normal acceleration may also be written in the form

$$\ddot{w}_i = \sum_k \psi_k (\ddot{q}_k)_i \tag{18}$$

it follows that

$$\sum_k (\ddot{q}_k)_i \int_A \psi_k \psi_j \, dA = -Q_i \int_A \bar{A}_i \psi_j \, dA - \dot{Q}_i \int_A \bar{\bar{A}}_i \psi_j \, dA \tag{19}$$

In view of Eq. (13), Eq. (19) becomes

$$(\ddot{q}_j)_i = -Q_i (W_{1j})_i - \dot{Q}_i (W_{2j})_i \tag{20}$$

where

$$(W_{1j})_i = \frac{1}{\mu_j} \int_A \bar{A}_i(s)\psi_j(s) \, dA$$
$$(W_{2j})_i = \frac{1}{\mu_j} \int_A \bar{\bar{A}}_i(s)\psi_j(s) \, dA \tag{21}$$

In order to avoid oscillations in the relation between generalized forces and acceleration obtained from Eqs. (9)-(11) as a function of frequency, as discussed in Ref. [1], the $(W_{1j})_i$ and $(W_{2j})_i$ terms $(j \neq i)$ will be neglected compared, respectively, to the $(W_{1i})_i$ and $(W_{2i})_i$ terms.

This assumption neglects coupling between surface expansion functions at all frequencies and allows Eq. (20) to be simplified to

$$\ddot{q}_i = -Q_i/R_{1i} - \dot{Q}_i/R_{2i} \tag{22}$$

in which

$$R_{1i}(\Omega_i) = 1/(W_{1i})_i \ , \ R_{2i}(\Omega_i) = 1/(W_{2i})_i \tag{23}$$

The first term on the right-hand side of Eq. (22),

$$\ddot{q}_{1i} = -Q_i/R_{1i} \tag{24}$$

is the real (inertial) part of the second derivative of the generalized coordinate, in phase with the applied pressure, and the second term,

$$\ddot{q}_{2i} = \dot{Q}_i/R_{2i} \tag{25}$$

is the imaginary (damping) component, 90° out of phase. It now remains to match, at selected frequencies, the results yielded by Eqs. (9)-(11) with those yielded by Eqs. (24) and (25).

Consider simple-harmonic motion, at frequency Ω_{1i}, involving the ith surface expansion function only. If the matrix λ is assumed to be diagonal, Eq. (9) may be satisfied by a diagonal matrix B with main diagonal terms B_i such that

$$\ddot{q}_{1i} - B_i\lambda_i \overset{\cdots\cdot}{q}_{1i} = -e_iQ_i + B_i\ddot{Q}_i \tag{26}$$

in which e_i, the ith main diagonal term of the diagonal matrix γ^{-1}, is given by

$$e_i = 1/\gamma_i \tag{27}$$

where γ_i is the ith main diagonal term of the virtual mass matrix. Since a steady-state excitation is being considered, Eq. (26) may be written

in the form

$$\ddot{q}_{1i} = -Q_i(e_i + B_i\Omega_{1i}^2)/(1 + B_i\lambda_i\Omega_{1i}^2) \tag{28}$$

In order for Eqs. (24) and (28) to yield identical results, at frequency Ω_{1i},

$$-Q_i(e_i + B_i\Omega_{1i}^2)/(1 + B_i\lambda_i\Omega_{1i}^2) = -Q_i/R_{1i}(\Omega_{1i})$$

or

$$B_i = \frac{1 - e_i R_{1i}(\Omega_{1i})}{[R_{1i}(\Omega_{1i}) - \lambda_i]\Omega_{1i}^2} \equiv B_i(\Omega_{1i}) \tag{29}$$

Consider now simple-harmonic motion, at frequency Ω_{2i}, involving the ith surface expansion function only. If the matrix ε is assumed to be diagonal, Eq. (10) may be satisfied by a diagonal matrix D with main diagonal terms D_i such that

$$\dddot{q}_{2i} - D_i\varepsilon_i\dot{q}_{2i} = D_iQ_i - h_i\ddot{Q}_i \tag{30}$$

in which h_i, the ith main diagonal term of the diagonal matrix α^{-1}, is given by

$$h_i = 1/\alpha_i \tag{31}$$

where α_i is the ith main diagonal term of the damping matrix. For the steady-state excitation being considered, Eq. (30) may be written as

$$\ddot{q}_{2i} = -\dot{Q}_i(h_i + D_i/\Omega_{2i}^2)/(1 + D_i\varepsilon_i/\Omega_{2i}^2) \tag{32}$$

In order for Eqs. (25) and (32) to yield identical results, at frequency Ω_{2i},

$$-\dot{Q}_i(h_i + D_i/\Omega_{2i}^2)/(1 + D_i\varepsilon_i/\Omega_{2i}^2) = -\dot{Q}_i/R_{2i}(\Omega_{2i})$$

or

$$D_i = \frac{[1 - h_i R_{2i}(\Omega_{2i})]\Omega_{2i}^2}{R_{2i}(\Omega_{2i}) - \varepsilon_i} \equiv D_i(\Omega_{2i}) \tag{33}$$

4. Positive Inertia and Damping - Allowable Fitting Frequencies

For the steady-state excitation, at frequency Ω, of the ith surface expansion function only, Eqs. (9)-(11) may be written as

$$\ddot{q}_i = -\frac{[e_i + B_i(\Omega_{1i})\Omega^2]}{[1 + B_i(\Omega_{1i})\lambda_i\Omega^2]} Q_i - \frac{[h_i + D_i(\Omega_{2i})/\Omega^2]}{[1 + D_i(\Omega_{2i})\varepsilon_i/\Omega^2]} \dot{Q}_i \tag{34}$$

in which $B_i(\Omega_{1i})$ and $D_i(\Omega_{2i})$ are given by Eqs. (29) and (33), respectively. If λ_i and ε_i do not vanish, Eq. (34) reduces to the PWA as $\Omega \to \infty$:

$$\ddot{q}_i = \lim_{\Omega\to\infty} - \left(\frac{\hat{i}}{\lambda_i\Omega} + h_i\right)\dot{Q}_i = -h_i\dot{Q}_i$$

and reduces to the VMA as $\Omega \to 0$:

$$\ddot{q}_i = \lim_{\Omega\to 0} - \left(e_i + \frac{\hat{i}\Omega}{\varepsilon_i}\right)Q_i = -e_i\, Q_i$$

If Eq. (34) is to produce positive inertia and damping at all frequencies Ω, the coefficients of Q_i and $\dot{Q}_i$ must be negative. Thus, if λ_i and ε_i are positive, positive inertia and damping are ensured by requiring $B_i(\Omega_{1i})$, $D_i(\Omega_{2i}) > 0$. From Eqs. (29) and (33) it then follows that

$$\frac{1 - e_i R_{1i}(\Omega_{1i})}{R_{1i}(\Omega_{1i}) - \lambda_i} > 0 \tag{35}$$

$$\frac{1 - h_i R_{2i}(\Omega_{2i})}{R_{2i}(\Omega_{2i}) - \varepsilon_i} > 0 \tag{36}$$

are, respectively, sufficient conditions for positive inertia and damping.

The inequality of Eq. (35) will be satisfied if the fitting frequency Ω_{1i} is such that $R_{1i}(\Omega_{1i})$ lies between γ_i and λ_i, i.e.,

$$0 < \lambda_i < R_{1i}(\Omega_{1i}) < \gamma_i \tag{37}$$

Similarly, the inequality of Eq. (36) will be satisfied if the fitting frequency Ω_{2i} is such that $R_{2i}(\Omega_{2i})$ lies between α_i and ε_i, i.e.,

$$0 < \varepsilon_i < R_{2i}(\Omega_{2i}) < \alpha_i \tag{38}$$

Since λ_i is the high frequency limit of the inertial part of Eq. (34) and ε_i is the low frequency limit of the damping part of Eq. (34) (both of which limits vanish in an exact solution), it is recommended that λ_i and ε_i be arbitrarily set to small fractions of γ_i and α_i , respectively. The fractions may be determined by comparing the frequency behavior of the inertial and damping parts of Eq. (34) with those of Eq. (22). Least squares fits of the type proposed in Ref. [3] may also be used to determine the λ_i and ε_i. Alternatively, experience may indicate that the matrices λ and ε should be chosen such that known steady-state results from acoustic computer codes are matched at low and high frequencies, respectively, while still maintaining the inequalities of Eqs. (37) and (38). In any event, the satisfaction of the inequalities of Eqs. (37) and (38) ensures positive inertia and damping.

If the inequalities of Eqs. (37) and (38) are satisfied, it may be readily shown that in a steady-state excitation at any intermediate frequency $\Omega(0 < \Omega < \infty)$, the inertia and damping yielded by Eq. (34) [or equivalently Eqs. (9)-(11)] are smaller than the corresponding quantities produced by the VMA and the PWA. A closer reproduction of the exact curve relating inertial generalized force and driving frequency might be obtained by introducing an additional fitting matrix in Eq. (9), enabling an additional point of the approximate curve to match that of the exact.

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An earlier version of the uncoupling technique referred to as the Inertial-Damping Collocation Approximation is shown to be improperly formulated, and a corrected, improved and simplified version is presented.

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